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OPTIMIZING FARM-ROAD ACCESS IN AGRICULTURAL LAND-USE PLANS: A GIS NETWORK EXPERIMENT FOR SAMARKAND REGION

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Abstract
A field can lie close to a road but have no usable entrance. A road along its boundary may be separated from it by a channel, lack an authorised connection or lead to a disconnected network. These distinctions matter to land-use planning because a geometrically convenient layout is not necessarily an operationally feasible one. GIS can organise the relevant evidence, but the access definition and comparison objective must be explicit [1–3].
The research questions are therefore deliberately separate: how much direct field coverage can a fixed length of added road provide; how does coverage differ from proximity and network-route length; and what land-accounting and cost consequences accompany the selected layout? The experiment uses a 1,000 × 1,000 m geometry. Its controlled results are distinct from any future measurements in a geographically located study window.

2. Conceptual basis and regional setting

Shortest-path analysis identifies a route through a graph with specified edge weights; it does not decide which absent links should be constructed. Dijkstra's

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algorithm provides the routing step for non-negative weights [1]. Candidate selection is a different network-design problem [2]. The present workflow first selects links for direct side adjacency, then measures routes and corridor footprint. Neither a cadastral right nor agricultural suitability follows from those geometric operations [3–5].

Samarkand Region is the intended application context, and the supplied location map identifies Pastdarg‘om and Juma (Figure 1). The regional map is reproduced without redrawing and is not used to infer local road lengths or field boundaries. No geographical position is assigned to the numerical square used below.

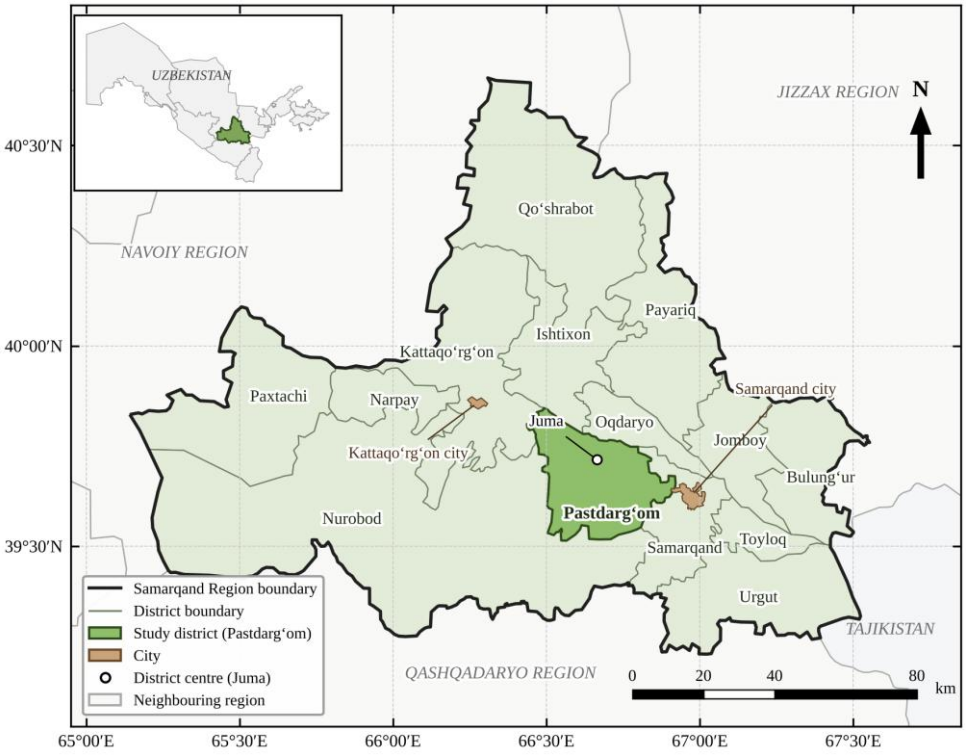

Figure 1. Regional setting: Pastdarg‘om District and Juma within Samarkand Region.

The design separates three evidence levels. The regional image supplies orientation only. The 100-ha benchmark supplies fully specified geometry and reproducible calculations. A later empirical application would supply authenticated fields, road

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connectivity, observed entrances, water crossings, rights and local costs. Regional accessibility rankings are not inferred from an illustrative background or from the benchmark's numerical values.

The four alternatives V0, V1, V1p and V2 are evaluated under the same field geometry and explicit cost assumptions. Centroid-distance summaries, corridor-width sensitivity and the model maps extend the access comparison without introducing different spatial inputs. All results are analytical calculations, not newly collected regional observations.

3. Materials and methods

3.1. A single field layer and four network alternatives

Table 1. Model inputs and interpretation limits.

Input	Specified value	Interpretation
Planning domain	1,000 × 1,000 m; 100 ha	Unlocated Cartesian metric square
Field geometry	10 × 10; 100 squares of 1 ha	No farm or ownership attributes
Existing roads	Four perimeter sides; 4 km	Connected baseline graph
Candidate roads	9 vertical + 9 horizontal; 1 km each	Full-length internal field boundaries
Depot	(0, 0) m	Hypothetical operational origin
Direct access	At least one complete side on a road	Geometric rule, not permission
Entrance	Best accessible side midpoint	No travel inside the field
Route weight	Segment length in metres	No speeds, slopes or closures
New-road corridor	4 m baseline; 6 and 8 m sensitivity	Declared assumptions, not design standards

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Table 2. Independent road-layout alternatives.

Variant	Added vertical lines, x (m)	Added horizontal lines, y (m)	Added length (km)
V0	None	None	0
V1	500	500	2
V1p	200; 400	None	2
V2	200; 400; 600; 800	None	4

Each field has a stable identifier, F001–F100, assigned in row-major order. All polygons are valid, each has an area of 10,000 m², their union is 1,000,000 m² and their overlap area is zero. Roads are noded at intersections and at 50-m intervals, which include every candidate side-midpoint entrance. Each variant is checked for graph connectivity. The perimeter makes the constructed networks connected; this is a benchmark property, not a general guarantee for real road data.

3.2. Road selection

Minimise $\Sigma_k \ell_k x_k$, subject to $b_i + \Sigma_k a_{ik} x_k \geq 1$ for every i; $x_k \in \{0, 1\}$. (1)
Here x_k selects candidate k, ℓ_k is its length, a_{ik} records whether it provides field-side adjacency, and b_i records baseline access. Exhaustive search evaluates every subset containing zero through four of the 18 candidates. The reported optimum is restricted to these complete straight lines; it is not a general optimum over all road designs.

3.3. Proximity, routing and land accounting

d_i = min distance(c_i, R); $s_i = \min_{e \in E_i}$ shortest-path distance(o, e). (2)
The first quantity uses field centroid c_i and the road centre-line union R. It measures straight-line proximity, not a traversable approach. The second uses depot o and the accessible entrance set E_i. If a field has no entrance, s_i is missing, not zero. Network distances are computed by Dijkstra's algorithm [1]. All-served means and a paired comparison for the same 36 baseline fields are reported separately.

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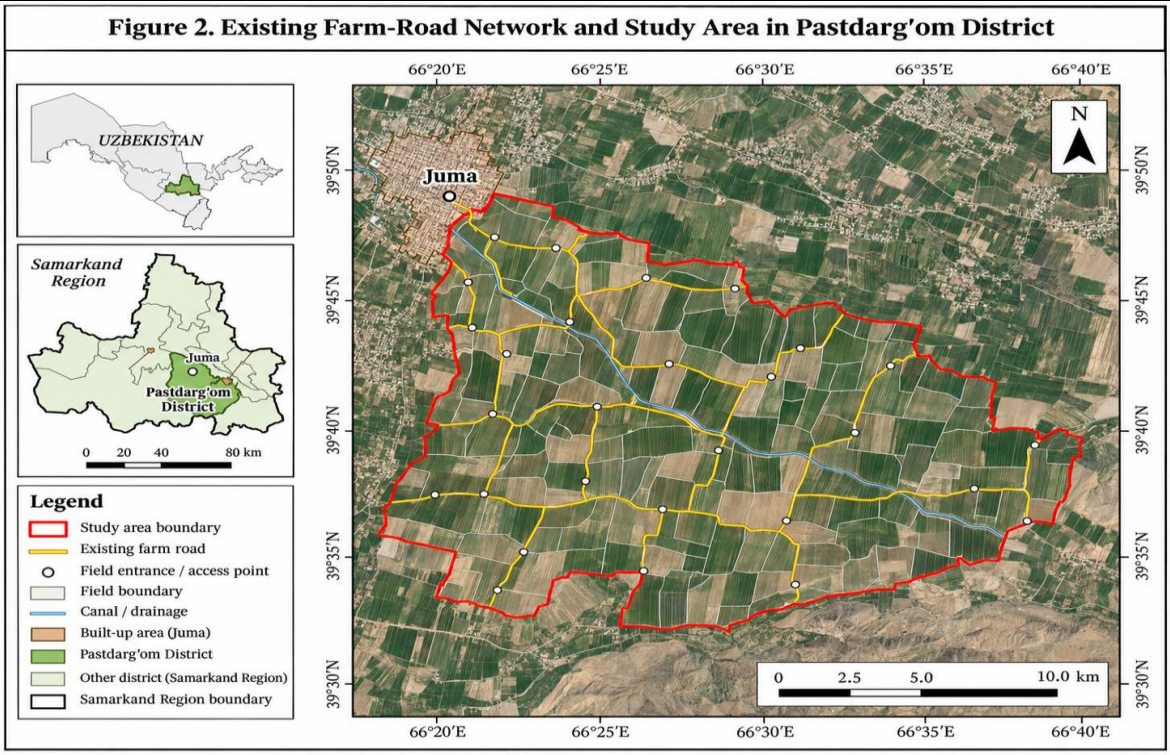

Figure 2. Existing farm-road network and land parcels in the Pastdarg‘om test area, overlaid on satellite imagery.

$C_N = 100N_served / N$; $C_A = 100\Sigma A_served / \Sigma A_all$. (3)

$A_road = area[union(buffer(R_added, w/2)) \cap B] / 10{,}000$. (4)

Count and nominal area coverage coincide only because all model fields have equal area. Equation (4) measures flat-ended new-road corridors of width w inside domain B. Buffer intersections are counted once. Existing perimeter-road land is not deducted. Original field areas remain fixed for the access experiment; corridor land take is a separate sensitivity output rather than an undisclosed change to the field denominator.

All computations were executed in Python using explicit vector geometry and graph analysis. The package contains source code, field-level CSV outputs and a GeoPackage with an engineering coordinate system in metres. The local geometry is constructed analytically; no satellite acquisition or geographically registered field delineation is used.

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4. Results and discussion

4.1. Proximity is not direct access

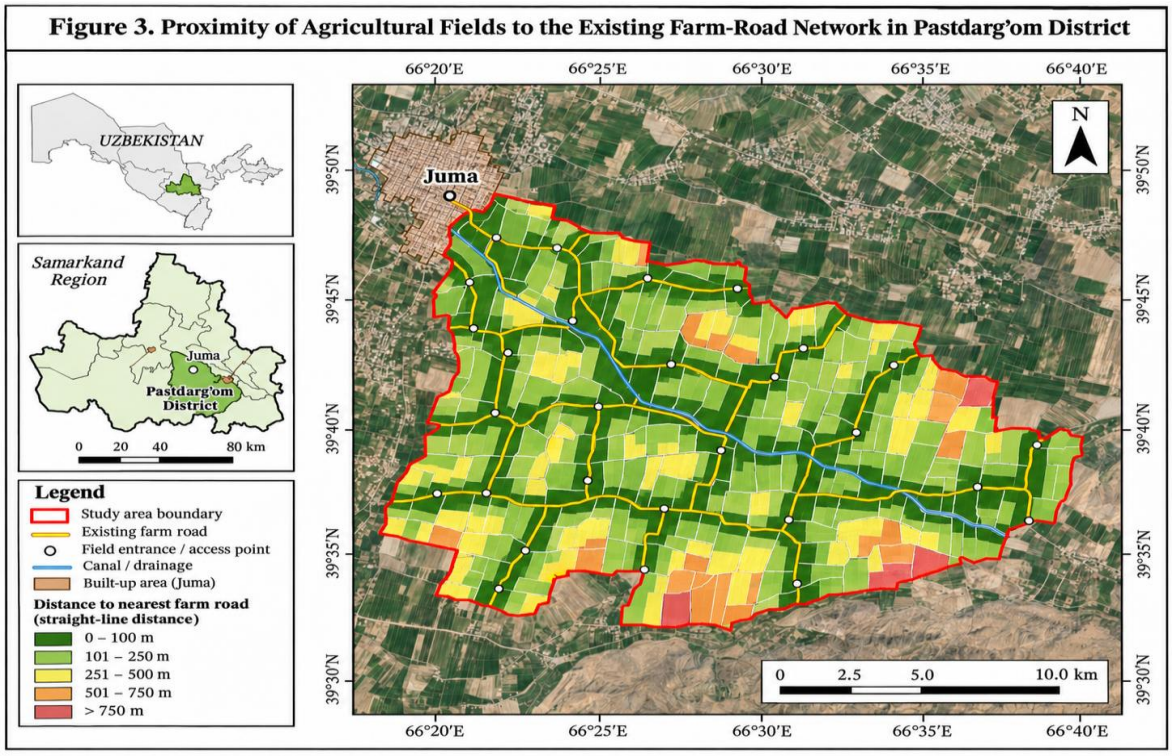

Figure 3. Proximity of agricultural parcels to the nearest farm road in the Pastdarg‘om test area.

Table 3. Field counts by centroid-to-road distance (new model diagnostic).

Distance class (m)	V0	V1	V1p	V2
0–100	36	64	68	100
>100–200	28	32	20	0
>200–300	20	4	12	0
>300–400	12	0	0	0
>400	4	0	0	0
Total fields	100	100	100	100
Mean distance (m)	170.0	90.0	94.0	50.0

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In V0, mean centroid distance is 170 m and the maximum is 450 m. After four parallel roads are added, every centroid lies 50 m from a road; the reduction in mean geometric distance is 70.59%. This is not a 70.59% reduction in operational travel because the centroid approach is not included in the routing graph.

The equal-budget alternatives expose a trade-off. V1 achieves a mean proximity of 90 m, compared with 94 m for V1p, yet V1p serves more fields directly. A criterion favouring the smallest mean centroid distance would select a different alternative from a criterion favouring maximum side adjacency. The map therefore provides a distinct diagnostic rather than a proxy for complete accessibility.

4.2. Network-based accessibility and paired routes

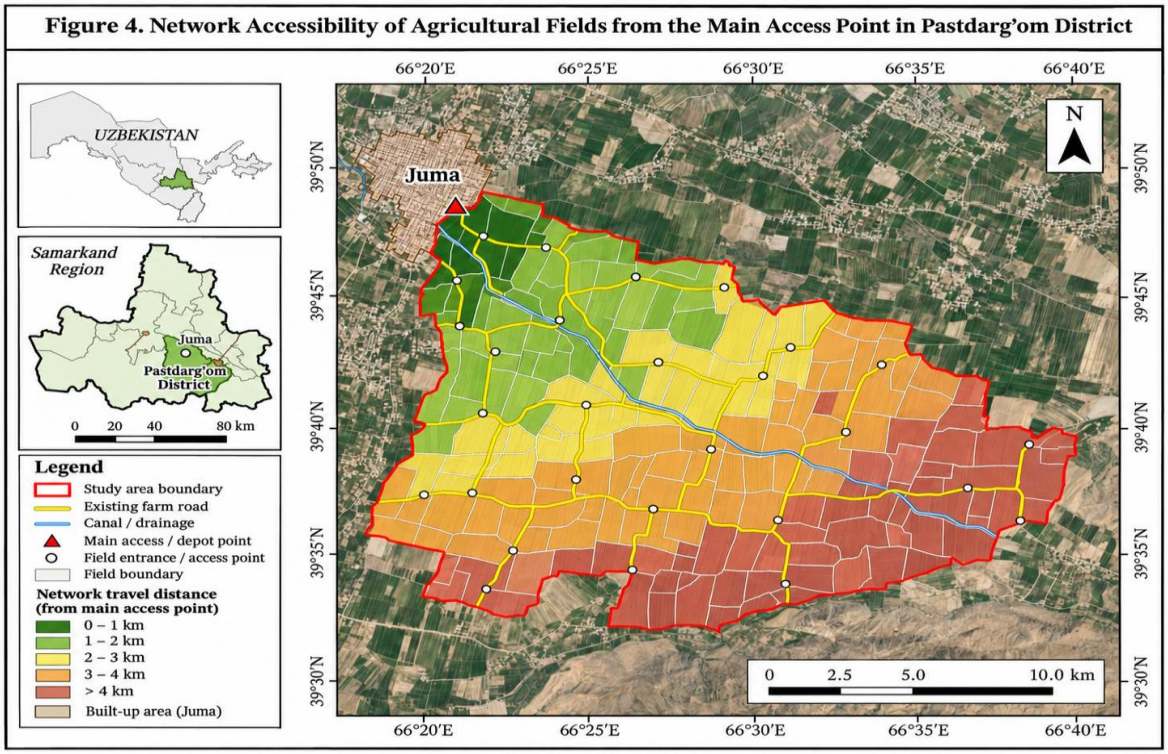

Figure 4. Network-based route-distance pattern for agricultural parcels in the Pastdarg‘om test area.

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Table 4. Recomputed access and route outcomes.

Measure	V0	V1	V1p	V2
Total road (km)	4	6	6	8
Additional road (km)	0	2	2	4
Directly served fields	36	64	68	100
Fields without an entrance	64	36	32	0
Mean route: served set (m)	997.2	993.8	901.5	995.0
Mean route: same 36 (m)	997.2	991.7	991.7	986.1
Median route: same 36 (m)	950.0	950.0	950.0	950.0

The 4-km perimeter provides direct access to 36 fields. V1 increases that number to 64; V1p provides 68 at the same added length. V2 provides all 100. Figure 4 explains route length using the same field F055 in both alternatives. Its centre is (450, 550) m. The V2 route ends at the side-midpoint entrance (400, 550) m; the 50 m from entrance to centre is not included in the 950 m road-network distance. The full and matched-sample summaries are reported in Table 4.

The comparatively low all-served mean for V1p, 901.5 m, is partly a sample-composition effect: the two added vertical roads are nearer the depot side. V1 and V1p nevertheless have the same mean of 991.7 m for the common baseline cohort. A comparison that omitted cohort definitions would therefore overstate what has been demonstrated about route efficiency.

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4.3. Mapping access gaps without inventing constraints

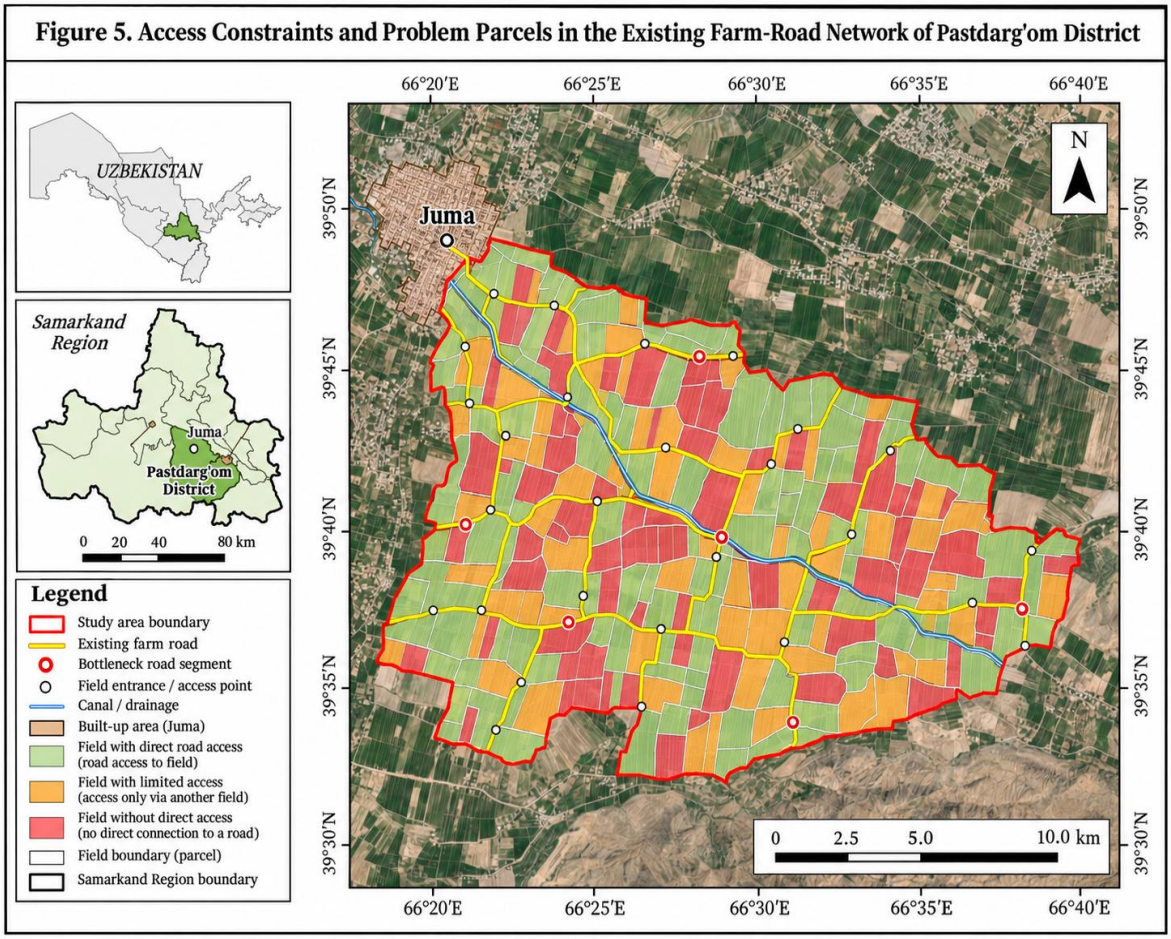

Figure 5. Access-gap map for agricultural parcels in the Pastdarg‘om test area.

The 64 interior fields in V0 lack an entrance because none of their sides belongs to the perimeter network. Some of them are near a road, but reaching it would require movement not included in the admissible graph. The gap map localises a precise model deficiency and makes it possible to test whether an added link resolves that deficiency. It does not explain the cause of a real access problem.

In an empirical dataset, at least three states should be separated: verified access, verified absence of a usable connection, and an unknown or uninspected connection. Assigning all missing observations to the second state would create an artificial access deficit. Conversely, snapping every nearby field to a road would

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assume entrances, permissions or crossings that may not exist. Entrance verification must precede claims about accessible agricultural area.

The model contains no channels, bridges, terrain restrictions or seasonal closures. These features are therefore not drawn on the gap map or treated as measured bottlenecks. Their absence from the model is not evidence that they are absent from the intended application area. A regional replacement should maintain Road_ID, Field_ID and Entrance_ID links, together with a documented status and source for each claimed barrier or connection.

The map suite distinguishes the physical question from the data-quality question: no model entrance is a computed condition under a stated rule, whereas unknown local access is a missing observation. Both may require further work, but they imply different planning decisions and should not share an unexplained map symbol.

4.4. Alternative configuration and restricted optimality

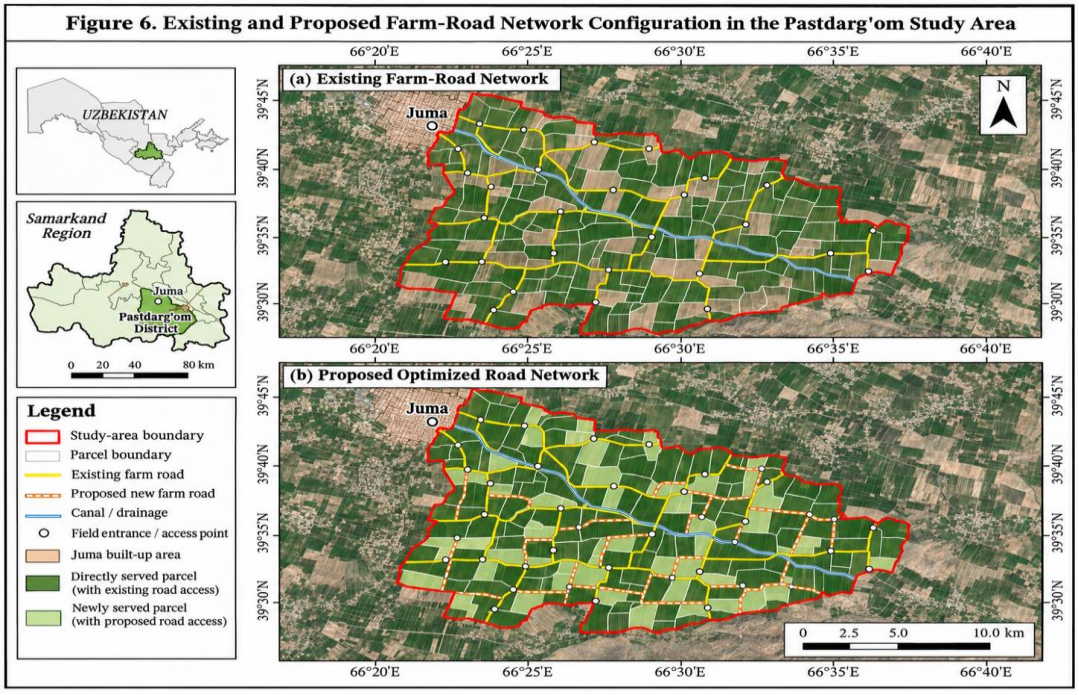

Figure 6. Existing and proposed optimized farm-road network in the Pastdarg‘om test area.

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Table 5. Maximum coverage from exhaustive candidate search.

Added km	Total km	Subsets tested	Maximum served	Maximising sets
0	4	1	36	1
1	5	18	52	14
2	6	153	68	30
3	7	816	84	20
4	8	3,060	100	2

All budgets together contain 4,048 subsets. Counts of maximising sets refer to the same fixed 18-candidate family.

At baseline, 64 interior fields are unserved. A complete internal road can add at most 16 previously unserved fields: the two boundary rows or columns already have perimeter access. Consequently, at least four candidates are necessary for full coverage. The four roads at x = 200, 400, 600 and 800 m attain that bound. Enumeration identifies two full-coverage four-road sets, the vertical and horizontal counterparts.

The proof and search agree, establishing optimality only for the defined family of full-length, equally weighted rectilinear candidates. Allowing short branches, different entrances, bridges, varying construction costs or additional constraints changes the feasible set. The label “optimal” must therefore state both the objective and its admissible candidate set, rather than implying a universally best farm-road plan.

4.5. Coverage expansion and route saving are different outcomes

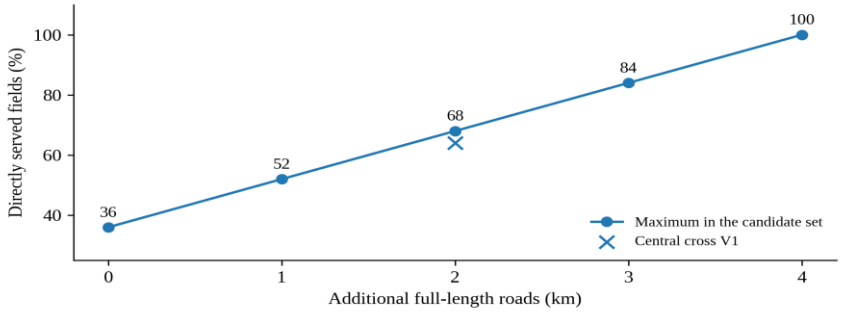

Figure 7. Maximum geometric coverage within the candidate family.

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The best attainable counts are 36, 52, 68, 84 and 100. The 64-field central cross is four percentage points below the 68-field parallel design at the same added length. The regular increments reflect the symmetric model; they should not be extrapolated as an expected return for each kilometre of road in a heterogeneous district.

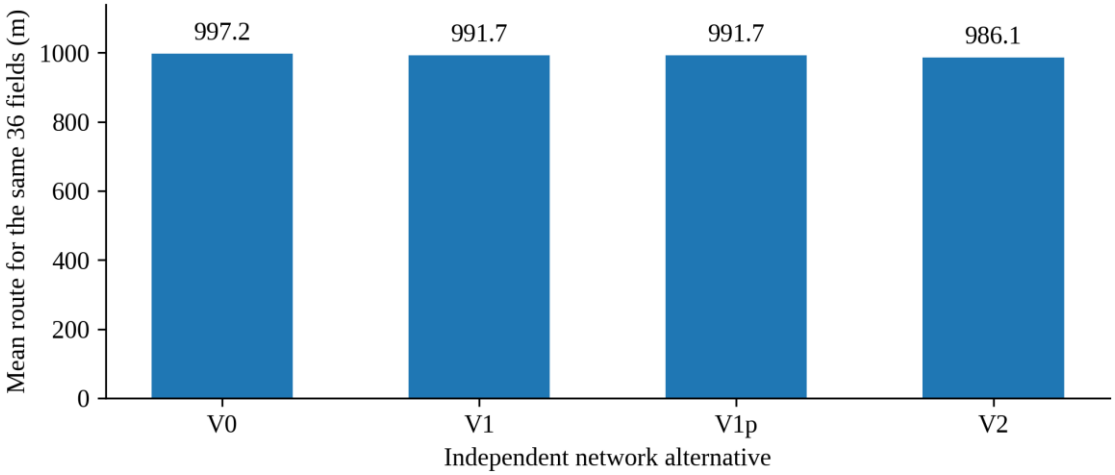

Figure 8. Mean shortest route on the same 36 baseline fields.

V2 reduces the matched mean from 997.2 to 986.1 m, an 11.1-m reduction or 1.11%; the median remains 950 m. In contrast, direct coverage rises by 64 percentage points. The objective primarily creates access for previously unserved fields. Presenting only the final coverage would hide the small matched-route effect; presenting only the small route saving would hide the expansion of access. This interpretation depends on the southwest-corner depot, length-based graph weights and side-midpoint rule. Different operational origins, multiple service centres or time-dependent road costs could change route results without changing the number of fields touching the selected roads. Such extensions require their own inputs and should not be silently incorporated into these totals.

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4.6. Corridor footprint and land-use trade-offs

Table 6. Added-road footprint under three assumed widths.

Alternative	Added km	4 m width (ha)	6 m width (ha)	8 m width (ha)
V1	2	0.7984	1.1964	1.5936
V1p	2	0.8000	1.2000	1.6000
V2	4	1.6000	2.4000	3.2000

Computed buffer unions, not observed road widths or engineering standards. The 6-m and 8-m cases extend the 4-m baseline calculation.

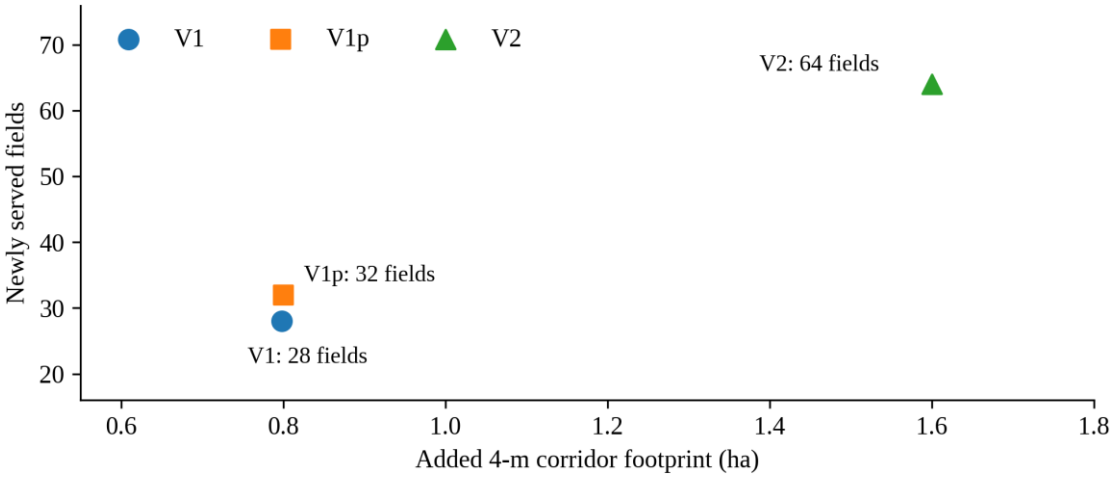

Figure 9. Newly served fields versus added 4-m corridor footprint.

For V2, four disjoint 1-km corridors of 4-m width occupy 1.60 ha. At 6 and 8 m they occupy 2.40 and 3.20 ha. The width changes the footprint but not the centre-line adjacency rule. The central cross requires 0.7984 ha at 4 m because its 16 m² crossing is counted once; two non-intersecting parallel roads require 0.8000 ha. The 0.0016-ha difference is a geometry identity, not an acquisition saving verified on the ground.

A land-use plan needs both the transport network and the polygon consequences of allocating road land. Here the original 100 one-hectare fields deliberately remain unchanged to make the access comparison transparent. The footprint table is therefore a separate land-accounting scenario. A construction design would

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subtract corridors from affected land, check residual field geometry, establish turning areas and crossings, and recalculate the production-area denominator.

No yield loss, compensation, drainage benefit or farm-income change is inferred from the buffer footprint. Those quantities depend on land rights, physical road design, cropping and operational evidence. A short line and a narrow corridor can be useful screening descriptors, but neither is a complete engineering or economic assessment.

4.7. Economic sensitivity under declared assumptions

$$E = 64b - 4c\,[r / (1 - (1 + r)^{-T}) + m]. \quad (5)$$

The economic experiment adopts the following declared assumptions: 64 newly served fields, 4 km of added road, a 10-year life, a 12% discount rate and annual maintenance of 2% of initial construction cost. Benefit b is expressed in million UZS per newly served field per year; cost c is million UZS per kilometre. Neither parameter is a verified local price or income estimate. The model does not value land acquisition, water crossings or existing-field route changes.

Table 7. Equivalent annual net outcome for V2.

Assumed cost c	b = 2	b = 4	b = 6	Break-even b
250	-69.0	59.0	187.0	3.078
400	-187.2	-59.2	68.8	4.925
550	-305.4	-177.4	-49.4	6.771

At c = 400, the annual-equivalent construction and maintenance cost is approximately 315.2 million UZS. Break-even requires about 4.925 million UZS annually from each newly served field. At the tested benefit of 4, the net outcome is −59.2 million UZS/year; at 6 it is +68.8. Complete geometric coverage therefore coexists with either an unfavourable or favourable assumed economic outcome.

The sign change is a useful methodological result. It prevents the map of a complete road network from being interpreted as proof of investment value. Actual appraisal

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would require field-operation frequency, equipment costs, seasonal usability, quantities and local construction rates. A bridge, compensation requirement or change in road width would alter the cost basis and must be carried through the same physical alternative rather than added only as a narrative caveat.

4.8. Subdivision, model dependence and transfer limits

The same 4-km perimeter serves 43.75%, 36.00% and 30.56% of fields in 8 × 8, 10 × 10 and 12 × 12 uniform grids, respectively. Full-length candidate logic requires three, four and five added roads for complete side adjacency. These algebraic sensitivities describe the benchmark family; they are not comparisons of real districts. They indicate that a road design cannot be evaluated independently of field subdivision.

The model also treats all fields as equal beneficiaries. For unequal field areas, count-based and area-based coverage would diverge, and a layout serving many small fields could have a different ranking from a layout serving a large production area. Differences in trip frequency could produce a third ranking. These are reasons to declare the planning objective, not to combine several unverified quantities into a single unexplained accessibility score.

5. Integration into district land-use planning

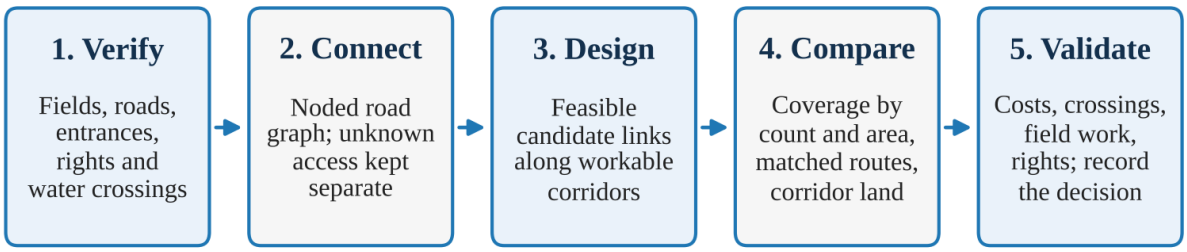

Figure 10. Editable workflow linking source verification to a land-use-plan alternative.

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5.1. Minimum evidence for a Pastdarg'om application

Table 8. Required empirical layers and their purpose.

Evidence	Required fields or checks	Planning consequence
Field polygons	Field_ID; date; area; valid geometry	Count and area denominators
Road network	Road_ID; connections; length; usability	Admissible network and weights
Field entrances	Entrance_ID; Field_ID; observed status	Verified versus unknown access
Water and terrain	Crossings, barriers and feasible gradients	Candidate exclusions and works
Rights and costs	Permissions; corridor width; quantities; prices	Legal feasibility and economic appraisal

The supplied regional map cannot provide these measurements. A real road map should use one dated fields layer, one verified road graph and one set of entrances across every alternative. Study-window dimensions must be measured in a documented metric coordinate system. A 2 × 2 km regional window has 400 ha and cannot be substituted for the present 100-ha model without rebuilding its inputs and recalculating the results.

5.2. From a model comparison to a feasible project

Candidate links should follow workable corridors and respect channels, existing infrastructure, land rights and turning requirements. For an irregular network, connectivity needs explicit checking or constraints; unlike the benchmark, a candidate may not automatically meet a connected perimeter. Unknown entrance status should be mapped separately from a confirmed physical barrier. The map suite must expose these distinctions rather than use road proximity as a substitute. The preferred alternative should retain a traceable record of its objective, affected fields, new entrances, corridor land, construction assumptions and rejected options. Existing users form the matched route cohort; newly served users form a separate coverage result. This separation supports a reviewable planning decision and

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prevents changes in the evaluated population from being mistaken for transport savings. It is consistent with treating spatial objects and rights as distinct components of land administration [6-13].

6. Conclusion

The experiment demonstrates that direct field coverage, geometric proximity, network routes and corridor land take are complementary rather than interchangeable measures. Within the specified 100-ha geometry, two parallel roads serve 68 fields at the same 2-km added-road budget for which a central cross serves 64. The central cross nevertheless has slightly better centroid proximity, showing that the ranking depends on the selected objective.

Four additional full-length roads are necessary and sufficient for complete geometric side adjacency within the 18-candidate family. Exhaustive enumeration and a simple coverage bound reach the same result. The mean route for the same 36 baseline fields falls only 1.11%, despite the increase from 36% to 100% direct coverage. Added 4-m corridors occupy 1.60 ha, and hypothetical economic outcomes change sign across the stated assumptions.

The methodological contribution is the consistent separation and reconciliation of these outputs using one field layer and explicitly defined network alternatives. The findings do not establish actual accessibility, field ownership, road construction benefits or investment returns in Pastdarg‘om. Empirical use requires verified geometry, entrance observations, constraints and costs; an engineering or legal decision cannot be derived from the benchmark alone.

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